Active Control of Open Cavities

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Introduction

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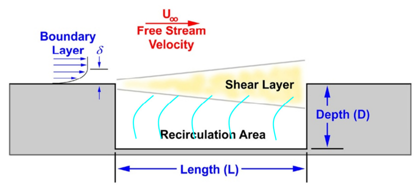
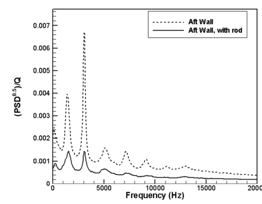
- Cavity flows (weapons bays, wheel wells, etc…) display intense aeroacoustic phenomena which after over 50 years of study still have several open questions especially as one tries to control them
- Current “point” design/retrofits solutions for aircraft will not be viable in the future
- Current efforts include;
  - Development improved methodologies viable for active flow control
  - Assessment leading edge suppression concepts which work well and examine there effects on the flow field
  - Extension to three dimensional cavities

Goal: Develop a better understanding of the flow field effects from successful applications of flow control for the reduction of surface pressure fluctuations in open cavity flows.

- Flow over open cavities represents a complex problem with many fundamental and applied examples and are governed by many parameters. Evaluations of control can not be based solely on the rms pressures on the surface or tonal reductions.



- Control schemes must have the ability to reduce broad band levels as well as tones similar to results that have been shown without active control.

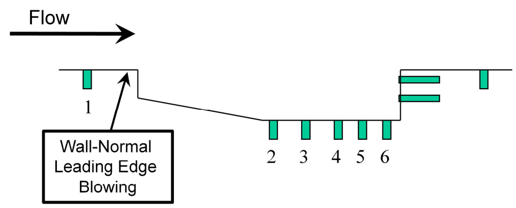


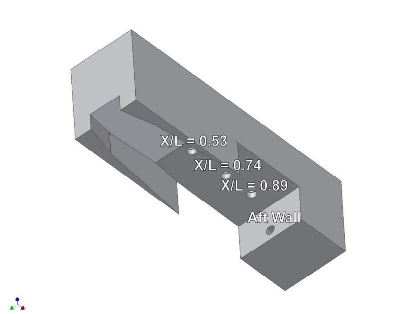
Need to work on wording of bullet items

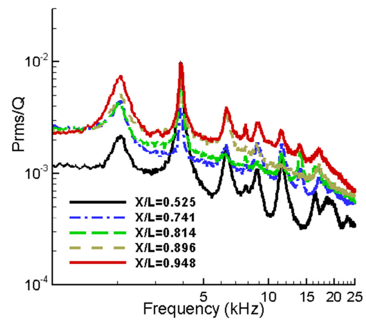
- Control Goals
- Open Loop Studies
- Closed Loop Studies

Open Loop Leading Edge Blowing

- Free Stream Mach # 1.5
- Stagnation Pressures
  - Po=15, Q=1820 psf
  - Ranges of Q up to 2200 psf
- 1.8 mm Boundary Layer at Cavity Leading Edge

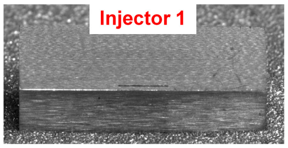


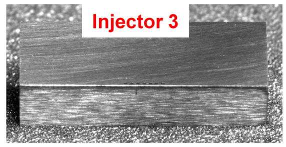


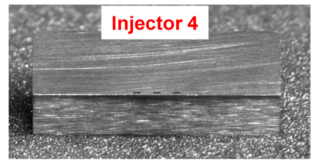


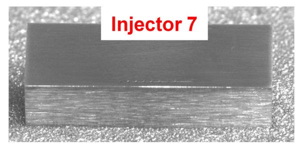
Ukeiley et al., Journal of Aircraft 2008

Leading Edge Slot Configurations Investigated





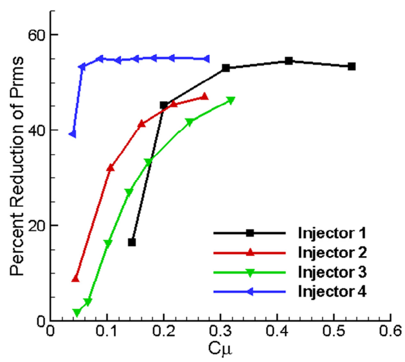




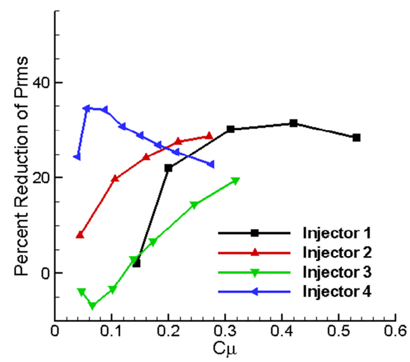
Injector	# of slots	Angle	Width	Length	Area
1	1	90°	0.01”	0.402	0.00402
2	4	90°	0.01”	0.025	0.00100
3	7	90°	0.01”	0.025	0.00175
4	3	90°	0.01”	0.058	0.00174
5	3	0°	0.01”	0.058	0.00174
6	3	45°	0.01”	0.058	0.00174
7	8	90°	Radius =0.008”		0.00161

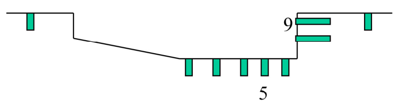
Reductions vs. Blowing Rates

x/L=1, Sensor 9



x/L=0.896, Sensor 5

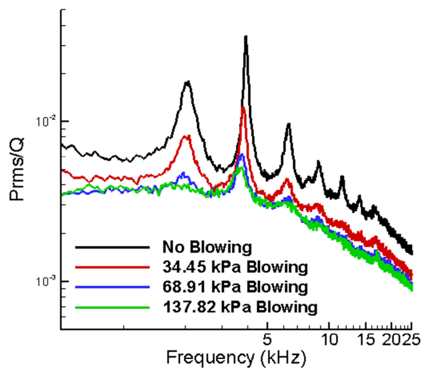




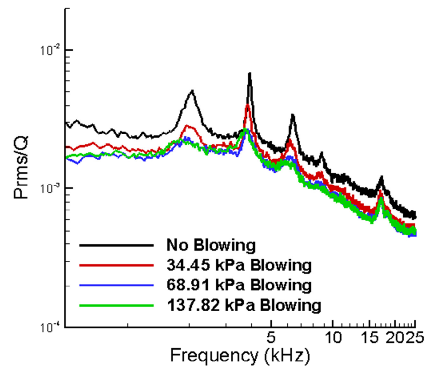
$$C_\mu = \frac{N m_{jet,tot} U_j}{{}^1\!/_2\, \rho_\infty U_\infty^2 w \delta}$$

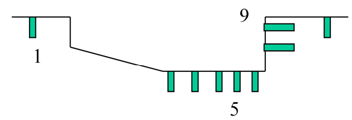
Narrowband Spectra

x/L=1, Sensor 9

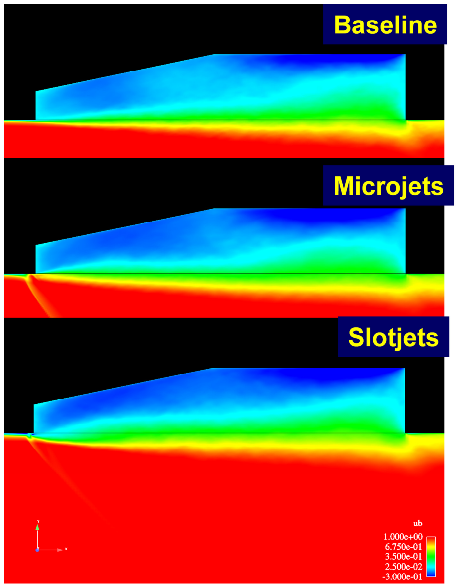


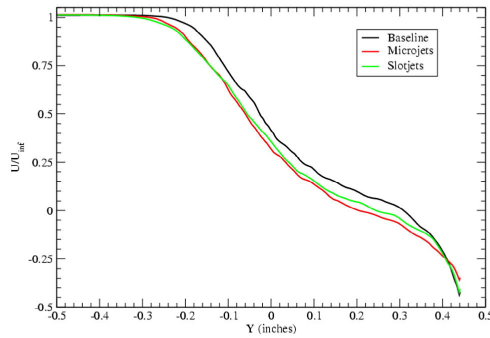
x/L=0.896, Sensor 5

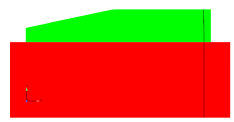




Mean U Velocity

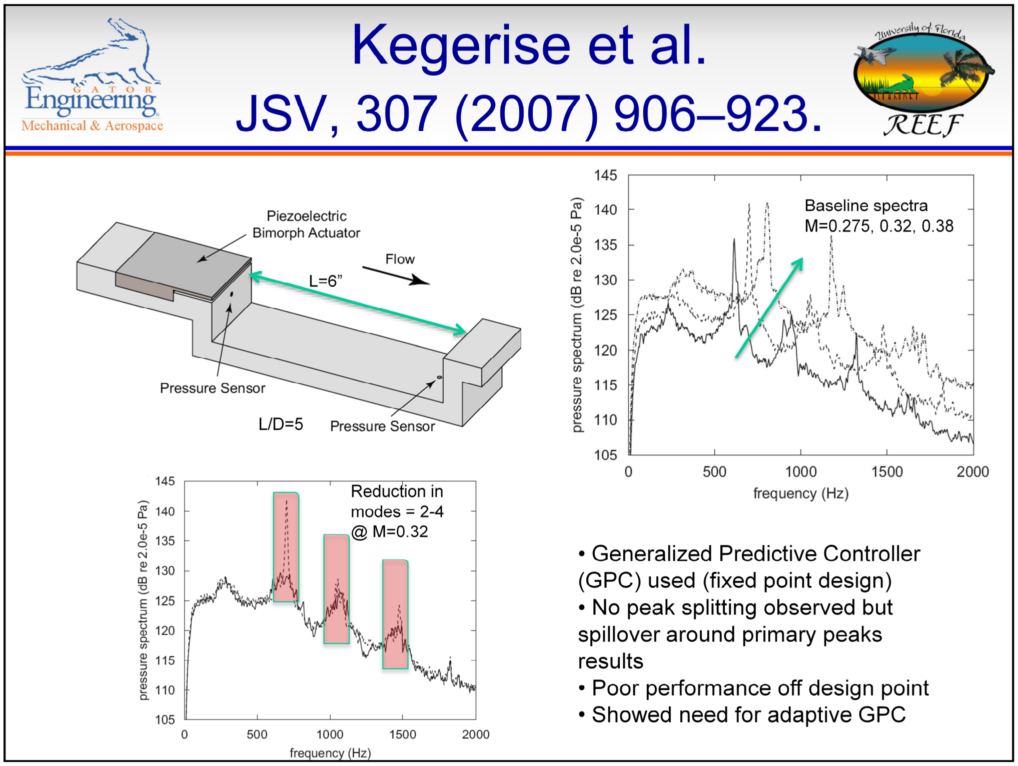






Arunajatesan et al., 2008

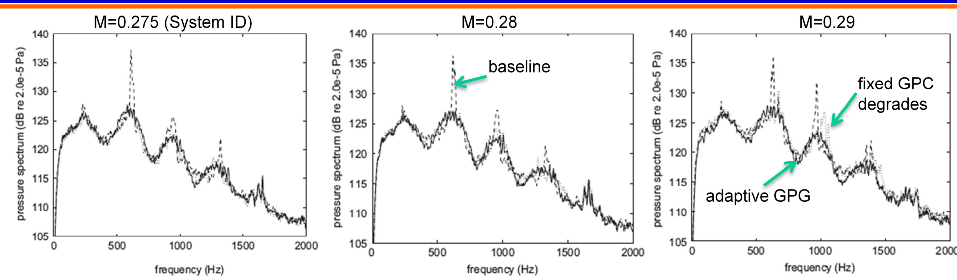
- Control Goals
- Open Loop Studies
- Closed Loop Studies



A generalized predictive control (GPC) algorithm was formulated and applied to the cavity flow-tone problem. The control algorithm demonstrated multiple Rossiter-mode suppression at fixed Mach numbers ranging from 0.275 to 0.38.

Controller performance was evaluated with a measure of output disturbance rejection and an input sensitivity transfer function. The results suggest that disturbances entering the cavity flow are collocated with the control input at the cavity leading edge. In that case, only tonal components of the cavity wall-pressure fluctuations can be suppressed and arbitrary broadband pressure reduction is not possible with the present sensor/actuator arrangement. In the control-algorithm development, the cavity dynamics were treated as linear and time invariant for a fixed Mach number. The experimental results lend support to that treatment.

Kegerise et al.
JSV, 307 (2007) 924–940.



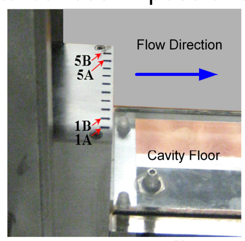
- Progressed to Adaptive Generalized Predictive Controller (AGPC) vs. fixed-gain GPC
- Plant model obtained using system ID at M=0.275
- AGPC suppressed multiple Rossiter modes at fixed Mach numbers of 0.275, 0.32, and 0.38, provided the plant model was updated for each Mach number
- AGPC maintains suppression of multiple cavity tones as the freestream Mach number was varied over a modest range (0.275–0.29)
- Adaptive plant model and control required for stable operation over wider range
- AGPC limited by spillover in sidebands around the suppressed Rossiter modes

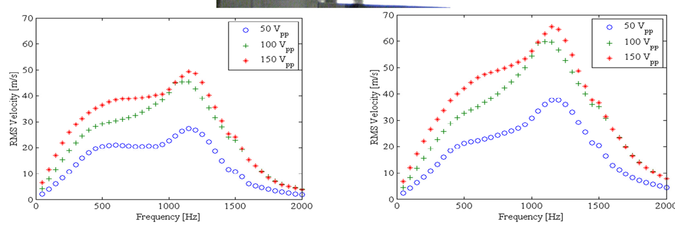
An adaptive generalized predictive control (GPC) algorithm was formulated and applied to the cavity flow-tone problem. The algorithm employs gradient descent to update the GPC coefficients at each time step. Past input–output data and an estimate of the open-loop pulse response sequence are all that is needed to implement the algorithm for application at fixed Mach numbers. Transient measurements made during controller adaptation at fixed Mach number revealed that the controller coefficients converged to a steady state in the mean, and this implies that adaptation can be turned off at some point with no degradation in control performance. The control algorithm demonstrated multiple Rossiter mode suppression at fixed Mach numbers of 0.275, 0.32, and 0.38, provided the plant model was updated for each Mach number.

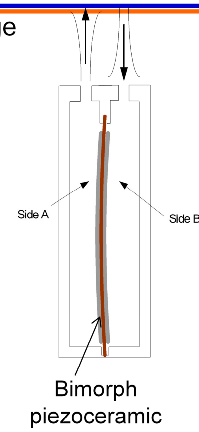
However, as in the case of fixed-gain GPC, the adaptive GPC was limited by spillover in sidebands around the suppressed Rossiter modes. The algorithm was also able to maintain suppression of multiple cavity tones as the freestream Mach number was varied over a modest range (0.275–0.29). Beyond this range, stable operation of the control algorithm was not possible due to the fixed plant model in the algorithm.

Song 2008

- Array (5x2) of ZNMF Dual Jets installed at cavity leading edge to generate 3D disturbances → possibility of broadband reduction?





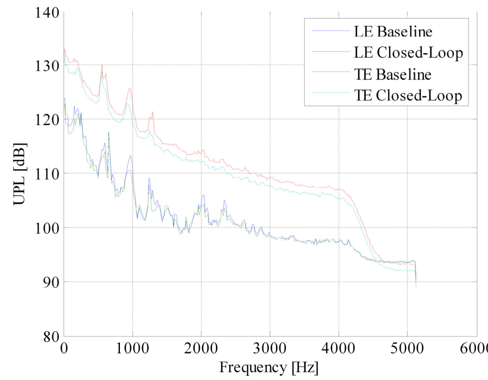


Hot-Wire Measurements of Actuator Velocities for #3

An array of 5 ZNMF actuators was installed at the cavity leading edge (which spans 2 inches). Each cell has 2 cavities. When the diaphragm moves to one side, it expels fluid from one slot and ingests fluid through the opposite slot. The design is self-venting, so dc pressure is equalized across each diaphragm (which prevents static deformation of the diaphragm for varying tunnel static pressure). The actuator produces peak rms velocities > 70 m/s (see next slide) over a bandwidth sufficient for suppression of Rossiter modes less than about 2 kHz.

Song cont'd…

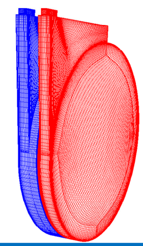
- Closed Loop Control
  - Mach 0.27
  - Adaptive System ID and GPC
  - Total Suppression = 3.3 dB
    - "Hybrid" control → reduces tones and broadband level using feedback
  - Future work to focus on understanding control mechanisms and limitations



Closed Loop Control Effectiveness

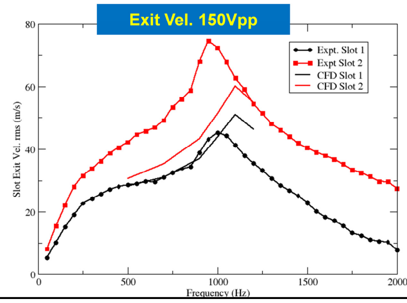
Modeling Approach (collab. w/ Craft Tech)

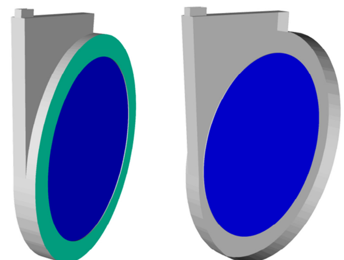
- Overall Approach (AIAA-2009-0743)
  - CFD model of Actuator and Surrounding Flow Field
  - Lumped Element Modeling (LEM) used to Compute Diaphragm Deflections
    - Surface Deflections used to Deform Diaphragm in CFD Calculation
  - Solver Computes Flow Field Generated by Actuator
    - Eventually Couple this with Cavity Flow Simulations for Control Applications.



CFD Model Of Single Actuator Cell

Exit Vel. 150Vpp





Exploded View

Multiphysics modeling of actuator to create a virtual test bed for control of cavity oscillations, in which the actuator is modeled in the Craft code w/ various closed-loop control algorithms. A key first step is to create a first-principles based code (described above) that accurately represents the ZNMF physics of the actuator. A few key points. First, in CL control, a sinusoid is not used so there is no simple way to impose ZNMF. Second, the model gives a reasonable representation of the benchtop measurements and enables us to determine what the CL control "needs" in terms of output from the actuator (since we are not limited by voltage in the simulations). Note the peak velocity > 70 m/s.

Summary/Future

- Open loop leading edge blowing was demonstrated as an effective method for reducing the broad band and tonal components of the fluctuating surface pressure in open cavities.
- Closed loop has been successfully applied to low Mach number open cavities.
  - Demonstrated the importance adaptive model coefficients
  - Demonstrated the importance of introducing three-dimensional disturbances
- Need to push actuators that are viable for closed loop control in bandwidth and output.
- Need a better understanding of the effects of control on the flow through detailed measurements so better actuation strategies can be developed.